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13. ABSTRACT *(Maximum 200 words)*

Acoustic phonons in quantum wells and quantum wires and various mechanisms of their interaction with electrons have been investigated. The obtained radiation patterns and spectrums for emitted acoustic phonons show that the thermal energy is radiated preferably in the direction of spatial quantization. The interaction of the electrons with confined acoustic phonons in free-standing quantum wells leads to the electron relaxation times having steps on their dependence on electron energy. The temperature dependence of the electron mobility is similar to that described by the Bloch-Grüneisen formula. Confined optical phonons in low-dimensional structures were shown to have unusual properties and to substantially affect the electron transport. The effects of phonon pumping and phonon drag in double-well tunneling heterostructure and the effect of transverse pattern formation in vertical tunnel transport in double-barrier heterostructure have been predicted and thoroughly investigated. The threshold-type scattering of electrons by acoustic phonons has been demonstrated to result in streaming of electrons in low electric fields and at low lattice temperatures. Photocurrent and excess current noise in quantum well infrared photodetectors has been investigated. The quantum well recharge under the influence of the nonuniform generated charge carriers drastically changes the dependencies of both photoconductive gain and excess current noise gain upon detector parameters.

14. SUBJECT TERMS

Low dimensional structures, free-standing structures, confined phonons, hot phonons, electron-phonon interaction, electron transport, electron noise, quantum well photodetectors.

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NONEQUILIBRIUM CARRIER DYNAMICS, TRANSPORT, AND NOISE IN LOW-DIMENSIONAL SEMICONDUCTOR STRUCTURES

FINAL REPORT

by

Vladimir Mitin

May 30, 1997

U.S. ARMY RESEARCH OFFICE

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WAYNE STATE UNIVERSITY

FOREWORD

Utilisation of low-dimensional semiconductor structures is strongly emphasized in modern microelectronics. State-of-the-art semiconductor technology permits fabrication of virtually perfect quasi-two-dimensional quantum wells. These structures are now being applied to the fabrication of field effect transistors, resonant tunneling diodes, avalanche multipliers, light detectors, spectral analyzers, light-emitting diodes and lasers, and other devices suitable for high speed microelectronics and optoelectronics applications. Quasi-one-dimensional quantum wires are expected to be even more promising, since the possibilities exist to suppress the electron scattering and to essentially enhance the charge carrier mobility.

In order to design perspective devices based on low-dimensional structures, it is necessary to get a complete qualitative picture of electron behavior in these structures, especially under realistic nonequilibrium conditions, as well as quantitative estimates of various characteristics such as transport and noise parameters, energy dissipation and momentum relaxation rates, recombination rates, etc. This project was aimed at filling the considerable gap between spectacular effects of pure quantum behavior of electrons in special experimental situations and the charge carrier properties in realistic devices. The aims of the research project have not been modified from original application. We strongly believe that all major goals of our project are achieved, so that the project is successfully accomplished.

We are grateful to the United States Army Research Office for opportunity to work in the forefront area of microelectronics and solid state physics and to train students in this area.

1 REPORT OF ACCOMPLISHMENTS

1.1 Problem

The strategic goal of our project was to provide theoretical background for utilizing low-dimensional semiconductor structures for high speed, low noise, and high efficiency performance.

In pursuing this goal we have investigated in detail three major interrelated topics. They are semiclassical transport, noise, and relaxation and recombination in quasi-equilibrium and strongly nonequilibrium two-dimensional and one-dimensional electron gases. Our main purpose was to gain an insight into carrier dynamics in low-dimensional structures under strongly nonequilibrium conditions (external fields, thermo- and photoexcitations), and to find eventually favorable structure parameters, external conditions, and regimes of operations for microelectronic devices based on these structures.

1.2 Summary of major results

Our investigations of the charge carrier dynamics in low-dimensional structures have main-

ly concerned the structures based on GaAs, because this material is being actively studied experimentally and it provides the technology for the best commercial heterostructures fabricated so far. We pay the most of our attention to the electron scattering by acoustic and optical phonons, which eventually determines the performance of microdevices.

The research on electron scattering, transport, and noise in low dimensional structures has been concentrated along the following directions (the referred list of publications is organized in inversed chronological order)

- Acoustic and optical phonons in low-dimensional structures and their interaction with electrons [3, 10, 20, 24, 31, 32, 33, 36-40, 49, 50, 53, 55, 57, 58, 61, 62, 64].
- Spectrum of acoustic phonons in free-standing quantum well and their interactions with electrons [5, 6, 7, 12, 17, 23, 41-43, 47, 63].
- Confined optical phonons in semiconductor heterostructures and their effect on the electron transport [13, 27, 28, 34, 35, 48].
- Non-linear transport effects in double-well and double-barrier quantum tunnel heterostructures [25, 26, 29, 56].
- Strongly nonequilibrium electron transport and noise in low-dimensional structures [1, 2, 16, 18, 19, 21, 51, 54, 60].
- Processes of electron capture in quantum wells and quantum wires [4, 11, 14, 22, 52, 59].
- Electro-optical parameters and noise of quantum well photodetectors [8, 15, 30, 44-46].

The following briefly describes our progress and accomplishments for each of these directions.

Acoustic phonons in low-dimensional structures and their interaction with electrons

We have demonstrated that macroscopic vibration and deformation of the heterointerfaces provide an additional mechanism of electron scattering in quantum wells. This mechanism does not depend on the deformation potential constant and, in most cases, occurs to be stronger than the piezoelectric potential scattering. A significant feature of this new scattering mechanism is that electrons interact not only with longitudinal but also with transverse acoustic phonons. We have calculated the rate of transverse acoustic phonon emission by hot 2D electrons in quantum wells,as well as the energy and angular distribution of emitted phonons. Comparison to the piezoelectric mechanism of phonon emission was done.

By means of solving both the kinetic equations for electrons and phonons we have obtained acoustic phonon radiation patterns and acoustic phonon spectra due to electron – acoustic-phonon interaction in double-barrier quantum wells and quantum wires. We

have included effects of nonequilibrium electron distribution and stimulated emission processes. The acoustic phonon radiation patterns have strongly pronounced maxima in the directions close to the normal to quantum well. This anisotropy of the radiation pattern is explained in terms of possible electron transitions, electron distribution function, and the Hamiltonian of electron-phonon interaction. In particular, we have shown that simple assumption that emitted phonons always have a perpendicular wave-vector component of the order of $2\pi/a$, where a is the width of the quantum well, cannot explain the obtained strong anisotropy of the radiation patterns. The required explanation is resulted from much more detailed analysis. The emitted acoustic phonon spectra have maxima at energies $2\pi\hbar u/a$, where u is the sound velocity. If the electric field is strong enough, the radiation pattern has also strong asymmetry in the plane of the quantum well.

Spectrum of acoustic phonons in free-standing quantum well and their interactions with electrons

In our theoretical investigations of kinetic characteristics of the electron transport in free-standing quantum wells we took into account the quantization of acoustic phonons and rigorously treated the electron interactions with confined acoustic phonons. We have solved numerically the kinetic equation for the electron distribution function and obtained the electron momentum relaxation time and the electron mobility in both cases of nondegenerate and degenerate electron gas.

At high lattice temperatures the electron momentum relaxation time is very similar to that obtained in the test particle approximation. Its dependence on the electron energy has steps which occur at the threshold energies for the dilatational phonon modes, where an additional electron-phonon scattering channels appear. The first dilatational mode makes the main contribution to the electron scattering, the contributions of the zeroth and the second modes are also important, the third and the higher modes practically unnoticeable for the studied electron concentrations and quantum well width.

At lattice temperatures lower than the energy of the first dilatational mode the energy dependence of the electron momentum relaxation time demonstrates additional peaks which the test particle approximation fails to explain. These peaks are associated with the electron scattering by several lowest acoustic phonon modes, they occur near the Fermi energy in the degenerate case and in the energy range of the first dilatational modes in the nondegenerate case. The temperature dependence of the electron mobility is similar to that described by the Bloch-Grüneisen formula, however we obtained a smaller negative exponent in the low temperature region.

Confined optical phonons in semiconductor heterostructures and their effect on the electron transport

We have studied spatial propagation of interface optical phonons in semiconductor heterostructures. Starting from a quantum kinetic equation for the nondiagonal phonon density operator, we have derived the wave-packet presentation for the phonon amplitude. For small wave vectors, the group velocity determining the speed of the packet is shown to substantially exceed the speed of sound. So, in contrast to the bulk case, the wave

front can propagate a distance of several micrometers before the phonon decay.

To investigate the effect of nonequilibrium optical phonons on electron transport in $GaAs$ quantum well, we have employed self-consistent Monte Carlo technique for solving coupled nonlinear kinetic equations for electrons and optical phonons confined in the well. The simulations have been performed for 30 K lattice temperature and a wide range of applied electric fields. The substantial difference between the generation and decay times as well as the confinement itself lead to a significant growth of the nonequilibrium optical phonon population accumulated by the heated electron gas. We have obtained that, when the optical phonon accumulation (as well as reabsorption) is significant, it substantially affects the electron transport properties in the quantum well.

For low 2D electron concentrations the hot optical phonon distribution reflects the main features of the electron distribution it originated from, its shape is also shifted along the electric field. Thus the nonequilibrium phonon system preserves a certain directed momentum in the opposite to the electric field direction. However, the optical phonon distribution function feedback on electrons is not essential, the electron and phonon systems are almost independent in this case.

For high (nondegenerate) electron concentrations due to increased hot phonon emission and reabsorption the nonequilibrium phonon distribution intensively spreads out in the quasimomentum space and practically loses its forward-peaked anisotropy. Interacting with the 2D electron subsystem the phonon subsystem behaves more likely as an isotropic distribution. Such a randomized hot optical phonon distribution influence on electron transport in the QW is reflected by the increase of high energy electron population (increase in the mean electron energy or electron subsystem temperature) and the decrease of the carrier drift velocity.

Non-linear transport effects in double-well and double-barrier quantum tunnel heterostructures

We have studied also the effects of electron-phonon interaction for several specific nanostructures. In particular, we considered the modulation of the electron properties of the tunnel-coupled quantum wells. We have calculated two main characteristics of linear electron response to the phonon pumping, phonon-induced voltage (i.e. induced dipole moment) and phonon-drag effect, as functions of the level splitting, electron concentration, and the scattering asymmetry. The results are substantially different for the cases of low and high electron concentrations. Taking into account intra- and interwell relaxation of electrons caused by asymmetrical interface roughness scattering, we have discussed the modulation of the longitudinal electron conductivity for different excitation regimes, made the numerical estimations for typical structure parameters, and suggested possible applications of double quantum wells as phonon detectors with high energy resolution.

We have carried out thorough theoretical investigation of the effect of pattern formation in the plane transverse to the tunneling current in resonant tunneling double-barrier heterostructures. We have shown that such patterns arise in heterostructures with intrinsic bistability of the current–voltage characteristic. The patterns are characterized by alternating position of the resonant level in the quantum well, nonuniform distribution of resonant electrons in the quantum well layer, and nonuniform tunneling current

density through the heterostructure. The effect considerably involves the lateral carrier transport and exists for both, coherent and sequential mechanisms of resonant tunneling. Possible types of these stationary patterns depend on the applied voltage and can be controlled by conditions on the edges of the heterostructure. In fact, the patterns occur to be three-dimensional in character, since the nonuniform in-plane electron distributions induce complex configuration of electrostatic potential in the barrier regions. Beside the stationary patterns, we have predicted the moving ones, which appear during the switching of the heterostructure from one uniform state to the other.

Strongly nonequilibrium electron transport and noise in low-dimensional structures

We have performed extensive Monte Carlo simulation of various transport phenomena in quantum wells and quantum wires.

Hot (nonequilibrium) phonon effects on electron transport in single and coupled quantum wires have been investigated by means of self-consistent Monte Carlo simulation. We have demonstrated that at room temperatures hot optical phonons lead to significant increase in electron drift velocity. This hot phonon drag effect is due to strongly asymmetric nonequilibrium phonon distribution. As a result, phonon absorption for forward transitions (electrons gain momentum along electric field) is enhanced, whereas absorption for backward transitions (electrons gain momentum against electric field) is suppressed. At low temperatures diffusive heating of electrons dominates over hot phonon drag and electron drift velocity decreases. For quantum wires coupled through common phonon system, electron transport in one wire affects considerably electron transport in another wire. In quantum wires with substantially different electron concentrations and opposite electric fields hot phonons cause the negative differential conductivity.

We also applied the Monte Carlo technique to investigate a nonlinear electron transport in quantum wires. It was demonstrated that the threshold-type scattering of electrons by acoustic phonons results in qualitatively new regime of the electron transport. This regime closely resembles the electron streaming. However, it is due to periodic acoustic-phonon emission, in contrast to conventional streaming caused by periodic emission of optical phonons. The reported streaming occurs at low lattice temperatures in wide range of electric fields and is characterized by an oscillating velocity autocorrelation function and a nonlinear velocity-field dependence. Both the analytical model and the Monte Carlo simulation yield an $E^{1/5}$ field dependence of the drift velocity and an $E^{2/5}$ dependence of the mean energy as a function of electric field E in the streaming regime.

As an important problem in the kinetics of non-degenerate one-dimensional electron gas, we have thoroughly investigated the role of intra-subband triple-electron collision on electron relaxation times in quantum wires. (The binary collisions are known to give zero contribution to the carrier relaxation.) We have derived the scattering probabilities from the Lippmann – Schwinger equation for the transition matrix. The obtained relaxation frequency can reach a value of 10^{12}/s, comparable to that by other scattering mechanisms, and indicate the importance of the effect for the relaxation of one-dimensional electron gas.

Processes of electron capture in quantum wells and wuantum wires

We have calculated the rates of electron capture to a quantum well taking full account of quasibound two-dimensional states, which are localized in the vicinity of a quantum well at electron energies above the barrier. To find the net capture rates, we calculate the rates of capture, escape, and relaxation within the bound two-dimensional states, assisted by both emission and absorption of optical phonons by electrons with arbitrary positive initial energy, as well as elastic scattering on acoustic phonons and impurities. The contribution of strongly inelastic scattering on longitudinal optical phonons was found to dominate except for well widths corresponding to the entrance of a new bound state into the quantum well, where the impurity scattering with small transferred momentum plays the main role. We have explained the dependencies of the capture rates of the non-degenerate electrons on the well width and temperature.

Electro-optical parameters and noise of quantum well photodetectors

We have investigated photocurrent and excess current noise in a quantum well infrared photodetector, making use of a drift-diffusion model of charge carrier transport. The effect of quantum well recharge under the influence of the nonuniform generated charge carriers is explained. The recharging effect drastically changes the dependencies of both photoconductive gain and excess current noise gain upon detector parameters. We have found that for uniform generation both gains coincide. For nonuniform generation, noise gain is essentially different from the photoconductive gain. This distinction is of the order of 100% for the real device parameters.

The influence of the nonuniform photogeneration on the electric field distribution was considered for the photodetector under drift velocity saturation. We have found that spatial nonuniformity of photogenerated electrons due to attenuation of the infrared flux induces strong electric-field domains which formation is accompanied by degradation of the signal-to-noise ratio. We obtained that domain structures undergo realignment at certain threshold voltage as a result of feedback influence of the quantum well recharging on the photogeneration rates which in turn cause the additional electric-field redestribution. The realignment manifests itself in a step-like change of photoconductive gain and quantum efficiency of photoabsorption at threshold bias voltage and is followed by considerable increase of generation-recombination noise.

2. SCIENTIFIC PERSONNEL AND DEGREES

The following researchers have been supported from this grant:
Vladimir Mitin, Professor;
Ia Ipatova, Visiting Professor;
Rimvydas Mickevičius, Visiting Assistant Professor;
Nikolai A. Bannov, Assistant Professor (Research).

Two graduate students have received M.S. degrees during 1995, working on this project: Vadim Aristov (graduated in summer 1995) and Gediminas Paulavičius (graduated in winter 1995). Three Ph.D. degrees have been received: Nikolai Bannov (graduated

in fall 1994), Yury Sirenko (graduated in fall 1994), and Remis Gaska (graduated in fall 1996).

3. INVENTIONS

The following patent has been submitted: "Interchannel Nonequilibrium Confined-Phonon Exchange Device," by V. Mitin, V. A. Kochelap, R. Mickevicius, M.A. Stroscio, and M. Dutta, filed 9/1/95, No.8/522693.

4. TECHNOLOGY TRANSFER

We have submitted above cited patent on device based on phonon switching which is promising for new electronic applications.

5. LIST OF MANUSCRIPTS

5.1. List of papers in refereed journals

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41. "Photon Absorption by Free Electrons Due to Interaction with Confined Acoustic Phonons in a Free-Standing Quantum Well," N. Bannov, F. Vasko, and V. Mitin. Eight International Conference on Superlattices, Microstructures and Microdevices (ICSMM-8), Cincinati, Ohio, August 20-25, 1995, p. VIII.9.

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